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Urbanization and environmental policy effects on the future availability of grazing resources on the Mongolian Plateau: Modeling socio-environmental system dynamics

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ABSTRACT

The rangelands of the Mongolian Plateau are dynamic socio-environmental systems that are influenced by a complex network of drivers, including climate, social institutions, market forces, and national-scale policies affecting land access and management. The sustainability and resilience of rangelands in this region depend on the ability of residents and policy makers to quickly respond by adapting livelihoods and land uses to changes in environmental and socio-economic conditions, but the responses of the system to these changes are often non-linear and difficult to predict. We developed a system dynamics model to understand how the human, natural, and land-use processes in the Mongolian rangeland ecosystem interact to produce dynamic outcomes in both grassland productivity and livestock populations. We developed two separate models based on a common integrative framework for two case study areas: Suhkbaatar Aimag in Mongolia and Xilingol League in Inner Mongolia. We used future scenarios for each region generated with stakeholder input to forecast trends in grassland area, livestock numbers, and biomass under alternative climate, socioeconomic, and land-use futures. By incorporating stakeholder-developed scenarios, we were able to explore future scenarios tailored to the particular questions and concerns relevant to the individual study areas. We find that while there are many similarities in the factors driving system dynamics in the two countries, the trajectories of key grassland resources are quite different, both between the two study regions and across the individual scenarios. Environmental policies play a key role in Xilingol, while economic development is a key driver in Sukhbaatar. Urbanization dynamics will be a major influence on the availability of grassland resources in the future.

1. Introduction

Significant degradation is occurring across the world's arid and semi-arid rangelands (Maestre et al., 2016; Reynolds et al., 2007) and is projected to increase under climate change (Huang et al., 2015). The status of arid rangelands, which provide forage for 75% of the world's livestock, has implications for livelihoods, ecosystem services, and carbon storage, which can feedback to affect climate change. Thus, there is a real need to understand both the interacting factors affecting degradation as well as potential future restoration trajectories. We know that rangelands are socio-environmental systems (Liu et al., 2007; Chen et al., 2015a,b). To understand rangeland dynamics, particularly at landscape scales, we need to consider how societal and environmental changes affect rangeland biophysical conditions and, additionally, how those conditions feed back to affect decisions by individuals and government about livelihoods and policy. To evaluate the future sustainability of arid rangelands, data and models are needed to describe the natural and human components of these systems, their dynamics, and their interactions (Maestre et al., 2016).

The Mongolian Plateau is one of the world's largest areas of continuous arid rangeland, covering most of Mongolia and the Inner Mongolian Autonomous Region of northern China, and is a clear example of a coupled human-natural grassland system. The Mongolian Plateau was historically inhabited by pastoralists who migrated seasonally with livestock herds. Although the people of the region have a shared ecological and cultural history stretching back thousands of years, Mongolia and China have undergone

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significant socio-political changes over the past fifty years that have dramatically affected the environments and economies of the two countries (Chen et al., 2015a,b; Kawada and Nakamura, 2011; Wang et al., 2013a; Xie and Sha, 2012).

Rapid ecological and socioeconomic changes, including climate change, population growth, infrastructure investment, and sedentarization have been linked to significant grassland degradation in parts of the plateau (Hilker et al., 2014; Williams, 1996, 2000), although the universality of these links are contested (Kolås, 2014; Taylor, 2006). These changes have been particularly dramatic in the Inner Mongolia Autonomous Region of China, but recent socioeconomic and environmental changes in Mongolia have put increasing stress on the grasslands, particularly in the northern half of the country (NAMEM and MEGDT, 2015). Drivers such as rapid urbanization and spread of informal settlements in peri-urban areas, record high livestock numbers, and climate changes have also been identified as potential limits on future grassland resilience in Mongolia as well; there is debate about the relative impacts of each of those factors (Addison et al., 2012).

Across the Plateau, several dynamics could affect rangelands in the future. Rates of urbanization, i.e., migration of populations from rural to urban areas, are increasing (Fan et al., 2015); the climate is changing, becoming drier in some places, wetter in others, and more variable overall (NAMEM and MEGDT, 2015); and livestock herd sizes and composition are in flux (Huang et al., 2015). All of these dynamics have the potential to alter the ability of grasslands to sustain their function and continue to provide ecosystem services. The status of grasslands on the Plateau is unclear, with reports from Mongolia stating anywhere from 10% to 90% (Addison et al., 2012; Hilker et al., 2014; NAMEM and MEGDT, 2015) of the grazing lands are degraded to some extent.

In order to better prepare for the future, a better understanding is needed of how the human, natural, and livestock sectors interact to affect the rangelands on the Plateau. We adopted a system dynamics approach (Forrester, 1961; Scholl, 2001) to explicitly link the social, environmental, and land-use sectors and represent how their interactions affect dynamics in this arid rangeland system. System dynamics (SD) models facilitate learning about how a system changes over time in response to various shocks, and how dynamic feedbacks can lead to non-linear behavior in complex systems (Ford, 1999). While primarily developed for analyses of industrial systems (Forrester, 1994; Holmberg, 2000), SD models are also appropriate for trying to understand coupled human and natural systems (Rasmussen et al., 2012; Shen et al., 2009; Stave, 2010). Properly constructed, SD models can be run with different initial or boundary conditions to evaluate system behavior, or with alternative assumptions about future conditions (e.g., policy or climate). To date, few dynamic models have incorporated socio-economic, land use, and climate data together to evaluate these interacting influences on grassland systems (Herrmann et al., 2014).

We used SD models to evaluate the potential impacts of changes in policy, internal migration (urbanization), and climate on the trajectory of grassland biomass production and livestock populations on the Plateau. Given their contrasting histories, we focused our modeling work on comparing two representative case-study regions in Mongolia and Inner Mongolia, China. The basic framework for the models includes human, natural, and land use sub-models that are dynamically linked through key endogenous variables. Model details are based on a common conceptual structure but vary slightly between the two regions because of differences in the underlying socio-environmental conditions and in the data available to model them (Supp Fig. 1). Our model development, simulation, and analysis were aimed at improving our understanding of the potential for future resilience of rangelands on the Mongolian Plateau. We assessed resilience through three key variables that represent the socio-environmental status of the system: availability of grazing area (grassland cover), livelihoods (livestock population), and forage resources (biomass availability). We assess the potential for the region to continue to support livestock husbandry by addressing the following questions: How will grassland area respond to changes in policy, climate and the economy? How will urbanization affect the availability of grazing resources?

2. Methods

2.1. Study area

Our adjacent case study regions, one in China and one in Mongolia, are located centrally on the Mongolian Plateau; Xilingol League, China and Sukhbaatar Aimag (province) in Mongolia (Fig. 1). They share the international border and similar environmental conditions, but differ in their recent socio-political history.

Fig. 1. Location of the two case study regions, Xilingol League and Sukhbaatar aimag.

2.1.1. Xilingol

Xilingol League is located in central Inner Mongolia, approximately 400 km north of Beijing, and borders Mongolia to the north. A distinct aridity gradient extends east to west and divides the league into three grassland ecoregions from east to west, known respectively as the "meadow steppe," "typical steppe," and "desert steppe." The region's climate is temperate and arid, with a mean annual temperature of approximately 1 °C and an annual precipitation of 400 mm in the east, decreasing to less than 200 mm in the more arid southwest.

Land tenure and policies regarding resource rights in Inner Mongolia have shifted dramatically over the past thirty years. In the early 1980s, the Chinese government passed the livestock contract policy, which privatized livestock and transferred the responsibility for determining herd size to individual households (Chen et al., 2010; Li and Huntsinger, 2011). Subsequently, land was allocated to individual administrative districts (hots) and, finally in the 1990s, grazing lands were contracted to individual households (Briske et al., 2015; Li et al., 2007; Tachiiri et al., 2008). Livestock was also privatized to individual households at this time. The amount of land allocated to an individual household varied greatly by location and population density (Kolås, 2014). Privatization sharply reduced the mobility of herders in the region and, according to some, led to overgrazing within fenced areas (Briske et al., 2015; Jiang et al., 2006; Taylor, 2006). Additionally, Inner Mongolia has undergone extensive land conversion from grassland to cropland in the past three decades (Gao et al., 2006; Hill et al., 2014). The government has also implemented policies and incentives to encourage the settlement of herder families into rural villages.

By the late 1990s, extensive grassland degradation in many parts of Inner Mongolia was linked to sandstorms affecting air quality in Beijing and a loss of economic productivity (Lu et al., 2009; Yang et al., 2014). Policies geared toward protecting grasslands and limiting cropland expansion were initiated by the Chinese government in the early 2000 s in an attempt to slow grassland degradation in Inner Mongolia (Li and Huntsinger, 2011). These policies have been somewhat successful at promoting re-vegetation of desertified areas (Hu et al., 2012). However, it is unclear how effective such policies will be over the long term, given expected urbanization and changing climate patterns.

The steppe grasslands in Xilingol are still primarily used for grazing, but changes in land tenure, privatization of livestock, and incentives to settle in rural villages have resulted in declines in nomadic herding and the subsequent intensification of grazing in affected areas (Li et al., 2007). The drier western portion of the league has experienced extensive grassland degradation (Li et al., 2007). Grassland conversion to agriculture is occurring primarily in the relatively more mesic southeastern portion of the league. Urbanization rates in Xilingol are significantly lower than the rest of China, but the urban population is increasing steadily as people migrate from rural areas and from outside of Xilingol to access employment in cities. As of 2013 the population of Xilingol was 1.04 million and over two-thirds of the population resided in urban areas (Statistics Bureau of Inner Mongolia Autonomous Region, 2011).

Livelihoods have diversified both within and among households on the Plateau over the past 20–30 years, particularly in Inner Mongolia (Wang et al., 2013a). Some have turned to non-pastoral livelihoods, such as cultivation, or found alternative employment to supplement herding incomes (Wang et al., 2013a). This change in livelihoods and land-use practices has also been driven by an increase in ethnic non-Mongolians in Inner Mongolia, many of whom have no socio-cultural connection to herding.

2.1.2. Sukhbaatar

Sukhbaatar aimag is located on the southeastern border of Mongolia, directly adjacent to Xilingol, and approximately 550 km from the capital city of Ulaanbaatar. Sukhbaatar experiences a slightly less mesic climate, with an average of 185–215 mm of precipitation. Sukhbaatar is a predominantly rural region with a low population density. The population of the aimag (approximately 55,000 in 2013) is a full order of magnitude lower than Xilingol, but the livestock population in 2013 was nearly 4 million head. Despite this relatively low population density, the rangelands in Sukhbaatar have been experiencing moderate degradation, primarily in the southwestern portion of the aimag (NAMEM and MEGDT, 2015). Livestock herding is still the dominant livelihood in this area, but some herders have been diversifying their income as a strategy to deal with uncertain future climate (Wang et al., 2013a,b,c). Studies of herders' perceptions of climate change have highlighted that the most significant impact that they

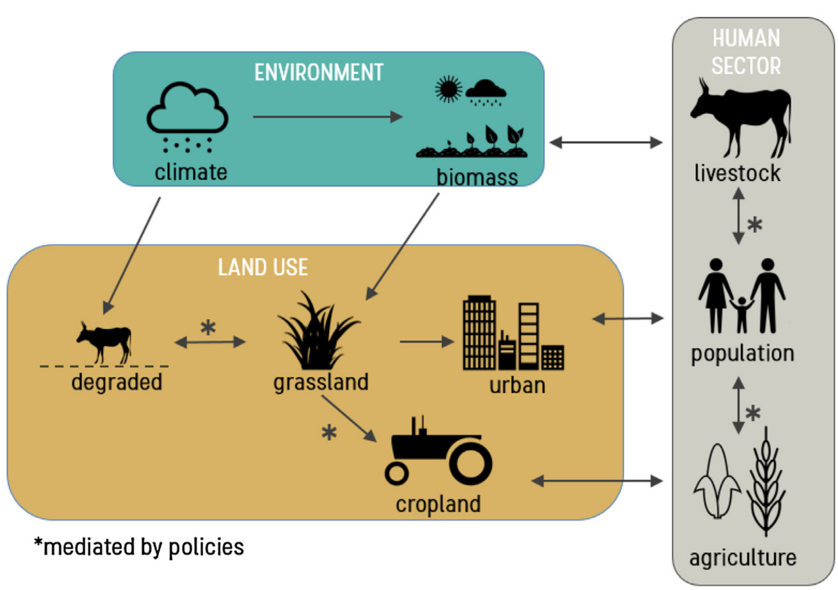

Fig. 2. Conceptual diagram of the structure of the system dynamics model for the Mongolian Plateau.

are experiencing comes from the droughts associated with the drier and more variable precipitation regime (Marin, 2010).

Contemporary policies regarding the rights of herders to access land in Mongolia are in flux. After the shift to a market economy in 1990, livestock were decentralized and allocated to individual herding families, or households. Many of the formal state-led institutions and herding collectives that oversaw livestock management were also dissolved (Addison et al., 2013; Fernández-Giménez et al., 2015). The centralized infrastructure to support livestock and herders during drought, long winters, or disease was no longer in place, with much of that responsibility now placed on the individual herder families (Fernández-Giménez et al., 2012; Wang et al., 2013a,b,c). At the same time, the government assigned decision-making power with regards to grazing access on communal lands to community-based councils and pasture user-groups or herder-groups. Many of these institutions were precipitated by external NGOs in response to perceived rangeland degradation in the late 1990s. These user groups can at times simply represent the codification of pre-existing familial partnerships, but at other times involve the partnering of formerly distinct households with no shared history (Fernández-Giménez et al., 2015).

There have also been several changes to policy in recent years to support growth in private markets. These changes have enabled the purchase of land under private title for use in cultivation. New policies and programs have supported the expansion of extractive industries, particularly mining (Amarjargal et al., 2015). The resulting land-use changes, while covering only a small area of the country, represent significant contributions to GDP (Mungunzul and Chang, 2016) and are evidence of a larger conversation in Mongolia today about the future direction of resource rights and land tenure (Undargaa and McCarthy, 2016).

2.2. System dynamics modeling

We modeled each case-study region as an interacting set of three subsystems: the human system (population and livestock change); the natural system (climate and grassland productivity); and the land-use system (conversions among grassland, cropland, urban land, and desertified land) (Fig. 2, but see Supplemental Fig. 1 for the full model schematic). System dynamics models represent the key variables in a system as a set of stocks and flows connected with causal loops. In the conceptual model (Fig. 2) the variables of human population and grassland are both stock variables, and the movement of people/land in and out of those stocks are the flows (represented by double lined arrows in the more detailed model structure shown in Supplemental Fig. 1). Independent exogenous variables provide inputs to the model; for example, climate variables such as precipitation or specific policy-related targets for biomass. The arrows connecting the shaded sub-system boxes in Fig. 2 are dependent endogenous variables that are responsible for the feedback loops and dynamism in the model, such as the impacts of climate and livestock on primary productivity and the estimated rates of urbanization, which affect the size of the rural labor force (arrows connecting urban area, human population and livestock in Fig. 2). See Supplemental Methods (including Supplemental Fig. 2) for a detailed description of the equations used to represent the relationships between endogenous variables in these three subsystems.

We estimated model parameter values based on a combination of: our own datasets and those of our collaborators (Chen et al., 2015a,b; Wang et al.,, 2013a,b); primary literature from the region (Baotana, 2011; Buhechaolu, 2005; Sun et al., 2010; Zhang et al., 2011); and data from census and statistical yearbooks (IMIGSD, 2011; Institute of Botany, 2011; Mongolian Meteorological Society, 2009; National Statistical Office of Mongolia, 2015; Statistics Bureau of Inner Mongolia Autonomous Region, 2011). We calibrated the model using data from 1990 to 2008, the timeframe for which consistent data on human and livestock populations and cropland area were available. Specific equations for model variables and values of model constants are given in detail in the Supplemental Methods.

Several key assumptions are built in to the base models. First, we assume a steady relationship between precipitation and net primary production, and utilized data from previous empirical and modeling studies in the region to specify the relationships in the

Table 1
Parameter settings for each scenario simulation for a) Xilingol League, Inner Mongolia and b) Suhkbaatar Aimag, Mongolia.

a) Xilingol

	Precip[a]	Grassland Protection Policy[b]	Cropland Policy[b]	Max Urbanized Fraction[c]
Baserun	Decline (-2)	On (1)	On (1)	Median level (0.75)
Scenario 1: Increasing Precipitation Trend	Increase (2)	On (1)	On (1)	Median level (0.75)
Scenario 2: No grassland protection targets	Decline (-2)	Off (0)	On (1)	Median level (0.75)
Scenario 3: No restrictions on cropland expansion	Decline (-2)	On (1)	Off (0)	Median level (0.75)
Scenario 4: No environmental policies, slower urbanization	Decline (-2)	Off (0)	Off (0)	Lower (0.60)

b) Suhkbaatar

	Labor Efficiency[d]	Grazing Intensity[e]	Market Access[f]	Out- Migration Rate[h]	Max Urbanized Fraction[g]
Baserun:	Moderate (0.02)	Moderate (1)	Moderate (1)	Slow declining trend: 700–> 500	Median (0.65)
Scenario 1: Industrialization/Urbanization	Low (0.01)	Moderate (1)	Moderate (1)	Steady at 700	Median (0.65)
Scenario 2: Rural Investment	High (0.03)	Low (0.25)	High (2)	Slow declining trend: 700–> 500	Median (0.65)
Scenario 3: Reduced Investment	Low (0.01)	High (1.3)	Low (0)	More rapid decline in out-migration: 700-> 150	Median (0.65)

[a] Coefficient to alter the slope of precipitation over time.
[b] Model switch to turn on (1) and off (0) protection policies.
[c] Maximum percentage of the population that is allowed to become urban by the model.
[d] Rate of adoption of new technologies and innovations to increase efficiencies in herding (resulting in larger hard sizes/individual).[e]Coefficient. Proxy for mobility. Higher coefficient = greater grazing intensity due to limited mobility in grazing strategies.
[f] Coefficient. Proxy for access to markets for sale of livestock, which can serve as a livelihood adaptation strategy.
[g] Coefficient to change the rate of urbanization within Suhkbaatar- higher coefficient = faster increase to max urban percentage.
[h] All migration out of Suhkbaatar (people/year), largely comprised of migration to Ulanbaatar.

model (Wang et al., 2013d). Recent work from other arid lands has shown that this relationship can shift depending on whether recent years were wetter or drier than average (Peters et al., 2013). Without consistent field data from across the region we were not able to incorporate the impact of historic trends. Second, we assume that the population of livestock is a function of the amount of labor available for herding. We used historic data on livestock and human population to describe this relationship, and summarize it as an increase in the number of livestock per herder over time. We attribute this to improvements in infrastructure and technology that would allow for greater herd sizes, and incorporate this slow increase in efficiency in the model. Third, we assume that households can be classified as urban or rural, but not both. Census data show that an increasing proportion of households in both countries are living in and around urban and developed areas. We recognize that it is not uncommon for some family members to move back and forth from rural to urban locales regularly; we do not represent this fluidity.

We ran each model for the period from 1991to either 2007 (Xilingol) or 2012 (Sukhbaatar), in order to observe fit between model output and historical trends. We assessed model fit against historical data for livestock population and human population for both regions.

We established baseline scenario projections by projecting the calibrated models forward to 2050, maintaining the same assumptions and parameter values used to build and calibrate the models (Table 1). We then compared those projected conditions to alternate futures, simulated by making changes in parameters values while maintaining the same relationships between them (Table 1).

2.3. Alternative scenarios

System dynamic models are not intended to provide point predictions of stock or flow variables. Rather, they are intended as a means to explore system behavior and make comparisons of behaviors produced under different scenarios. These different scenarios are simulated by changing the values for key parameters that can reflect potential changes in policy. Scenarios are most meaningful in pairs (or more), to enable comparison of the system-level effects of changes in parameter settings (Ford, 1999).

After establishing the baseline models, we developed a series of scenarios for each study area, based on plausible changes in immigration rates, policy, and climate that could create challenges to the sustainability of livelihoods and resilience of grasslands in each region. Each scenario was used to simulate the system to 2050 and evaluate the implications of parameter changes on the model projections for grassland area, livestock population, and biomass. The scenarios we developed incorporated input from a scenario-planning workshop held in Ulaanbaatar, Mongolia in 2014 with stakeholders and researchers from across the region (Ferdandez-Gimenez et al., in prep). We draw from scenario stories developed by two different groupings of stakeholders representing Inner Mongolia and Mongolia, respectively, to define the separate scenarios for the two case-study regions.

Mongolia and Inner Mongolia have very different states of development and degrees of government intervention and investment in policy and infrastructure. This requires different starting points in modeling the two regions. In addition, stakeholders from the two regions had distinctive concerns for the future, based on their knowledge and experience in each country. Inner Mongolia has experienced significant degradation of grasslands, strong government intervention in livestock husbandry practices, and has a population size that is an order of magnitude higher than that in Mongolia. Mongolia is experiencing rapid economic development and is in the midst of significant political and social negotiations over the future of land tenure, herding management, and mineral development. The future scenarios that the workshop participants developed, and that we test in this paper, reflect those different concerns.

2.3.1. Xilingol scenarios

The scenarios for Xilingol were focused on changes in climate, environmental policies, and demography. Four parameters within the base model were adjusted to simulate the conditions within each individual scenario (Table 1). The parameters were:

(i) the sign of the coefficient for the slope of precipitation over time (positive or negative);
(ii) a policy switch to turn on [1] or off [0] grassland and cropland protection policies, which trigger limitations on min/max size of that particular land-cover type;
(iii) the maximum urbanization percentage allowed in the model, which varied from 0.65–0.90 across the scenarios.

In *Scenario 1* we are interested in potential impacts due to predicted changes in climate as predicted for the region under IPCC climate scenarios (Xue-Jie et al., 2013; Yang et al., 2014). We simulate predicted future increases in Jan-July precipitation by changing the sign of the coefficient for the slope over time (Table 1). We modeled several different future climate scenarios by varying the trend, mean, and variability in precipitation. We present the results of a predicted increase in precipitation of over 40% by 2050 in Scenario 1 (Xue-Jie et al., 2013). For *Scenario 2,* we ended current policies that protect grassland area and promote restoration, in attempt to understand their effectiveness. We do this with a simple policy switch in the model which removes the target grassland area as an input. The predefined target grassland area in the model (based on regional governmental data) is used as a switch to initiate simulated grassland protection policies in the model (which slow crop expansion and remove grazing pressure) whenever grassland area falls below that target area. In *Scenario 3,* we removed any policy restrictions on cropland expansion through a similar policy switch.

Scenario 4, is a "*No Policy*" scenario, in which we assume a continued decline in precipitation (Wang et al., 2013b), removal of policies limiting cropland expansion and promoting grassland restoration, and a slowing of the rate of urbanization, which keeps the population more rural. This scenario explores the possible effects of a slowing Chinese economy. Table 1 compares the parameters that were changed across all scenarios, compared to the base model.

2.3.3. Sukhbaatar scenarios

The scenarios developed by stakeholders from Mongolia explored changes in urbanization, migration, and economic development. Four parameters within the base model were adjusted to simulate the conditions within each individual scenario (Table 1). The parameters were:

(i) Labor efficiency coefficient, which represents the relative rate of adoption of new technologies to increase efficiencies in herding (scaled from low [0.1] – high [0.3]) and modifies the number of livestock allotted per individual herder;
(ii) Grazing intensity coefficient, which serves as a proxy for mobility (scaled from low [0.25] – high [1.3]) and modifies the degradation rate;
(iii) Market Coefficient, which serves as a proxy for access to markets and modifies the livestock sale rate;
(iv) Out-migration rate, representing the movement of people from rural areas to Ulaanbaatar. This is set to increase, decrease, or remain steady depending on the scenario.

In *Scenario 1,* we increased the rates of rural-urban migration, both within Sukhbaatar and to Ulaanbaatar (resulting in decreased rural population as well as a decline in overall population for the aimag). *Scenario 2* represents enhanced practices to support rural infrastructure and mobility. This scenario assumed increasing market incentives and labor efficiencies in herding practices, with decreasing urbanization rates (due to increased incentives to maintain rural lifestyles) and reduced grazing intensities (due to enhanced coordination of mobility). We simulated this rural investment by increasing labor efficiency, decreasing the grazing intensity coefficient, and increasing the market coefficient (increased access to markets) in the model. We assumed that increased rural investment and access to infrastructure to support grazing would slow urbanization, and model this with a slower rural out-migration; the max urban fraction remained the same as the base model. *Scenario 3* continues current market trends toward privatization of resources and services, which we represent through a decrease in herding labor efficiency (due to loss of collective management institutions), and increase in grazing intensity (due to decreased mobility) and reduced access to markets for livestock (Table 1). We increased the rate of out-migration compared to the baseline model (Table 1).

Table 1 Parameter settings for each scenario simulation for a) Xilingol League, Inner Mongolia and b) Suhkbaatar Aimag, Mongolia.

2.4. Urbanization scenarios

Urbanization is simulated in each model via two main parameters, the fraction of the population that is urban at a particular point in time, and the maximum fraction of the population that can become urbanized (full details in Supplemental Methods) (Bocquier, 2005). The maximum (UF_s) is a constant that is adjusted according to scenario assumptions about the movement of people from rural areas to county centers and other developed areas and the livelihood activities in which people engage. In southern Mongolia, these settled areas are still quite small and rural, compared to county centers in Inner Mongolia. The rate of urbanization is responsive to this setting, such that the annual rate of movement of people from rural to urban areas is faster under higher assumed maximum fraction, and slower under a slower maximum (See Supplemental Methods). The Base models assume maximum urbanized proportions of 0.75 for Xilingol and 0.65 for Sukhbaatar, which reflect historic trends and a mid-range of future values based on current trajectories. In order to explore the sensitivity of the model to these assumptions about urbanization trends we simulated each Alternative Scenario under three different levels of urbanization (Table 2). An additional dynamic affecting Mongolia is the significant amount of rural out-migration of people from rural regions to Ulaanbaatar. For Sukhbaatar we also incorporated shifts in the relative rates of rural out-migration by altering the out-migration rate across the scenarios to simulate different rates of movement of people out of Sukhbaatar; this is a separate parameter from urbanized fraction which reflects the movement of people to settled areas within Sukhbaatar (Table 1b).

Table 2
Parameter settings for the assumptions under alternative scenarios of maximum fraction of the population that will become urbanized. Values for base scenarios for each region are underlined.

Case Study	Max Urban Percentage (UF_s)
Xilingol	0.60, <u>0.75</u>, 0.90
Sukhbaatar	0.55, <u>0.65</u>, 0.75

3. Results

3.1. Replicating historic trends

Simulated trends for livestock population and human population under the Base models corresponded well with historical data from Xilingol and Sukhbaatar (correlation coefficients = 0.71–0.95, $p < 0.01$ for all four comparisons; Fig. 3). Consistent with the historical data, the total area of grassland in the Xilingol simulation decreased in the 1990s, during the period of grazing intensification, stabilized through the early 2000s, then steadily increased over time after grassland protection policies were implemented around 2005 (Fig. 4a).

3.2. Base model projections

3.2.1. Xilingol

Projections of the base model simulations for Xilingol to 2050 revealed several long-term trends that could affect the availability of rangeland resources. Base model projections suggest the total area of grassland will continue to increase over time (Fig. 4a), but will never completely rebound to the level at the start of the simulation, due to the slow rate of natural succession and vegetative restoration in arid grasslands.

Cropland area in Xilingol remained fairly steady over time in the baseline scenario, due to the assumption that current policies that restrict agricultural expansion would continue (Fig. 4b). Policies were initiated in the early 2000s in an attempt to combat desertification due to overgrazing, which restricted livestock density, conversion of grassland to cropland and introduced subsidies. Livestock population dropped significantly after that time, which is reflected in the historic data as well (Fig. 3b). The population of livestock is predicted to continue to decline as well, largely due to urbanization, which results in a loss of rural population, and therefore a decrease in rural labor available for herding. Under the base model simulation, the population of livestock settles then fluctuates around five million sheep units by 2050, a decrease of over sixty percent from levels in 2000. Because of the decline in livestock numbers, the amount of biomass remaining at the end of the year (an inverse proxy for grazing pressure) is predicted to increase over time (Fig. 4c).

3.2.2. Sukhbaatar

The baseline simulation for Sukhbaatar projects a continued increase in livestock over time, along with a decrease in grassland area, and consequent reduction in available biomass (Fig. 5). This represents a continuation of trends occurring over the past decade (NAMEM and MEGDT 2015; Chen et al., 2015a, b) despite the decline in rural population. Within the long-term trend of increasing livestock, there are both short and long-term fluctuations, due to the occurrence of extreme weather events. Increased frequency and/or severity of dzud (extreme winters in Mongolia) has resulted in huge losses in livestock in recent years, but livestock populations have rebounded and continued to grow after each event. Model projections show continued rebounding of livestock populations following more frequent, intense dzud.

Grassland area is projected to decline under the baseline scenario. Declines in available grassland area are due primarily to degradation, driven by a combination of increased livestock numbers and insufficient precipitation in dry years. Available biomass also fluctuates greatly from year to year due to variability in net primary productivity in response to fluctuations in precipitation (Fig. 5c).

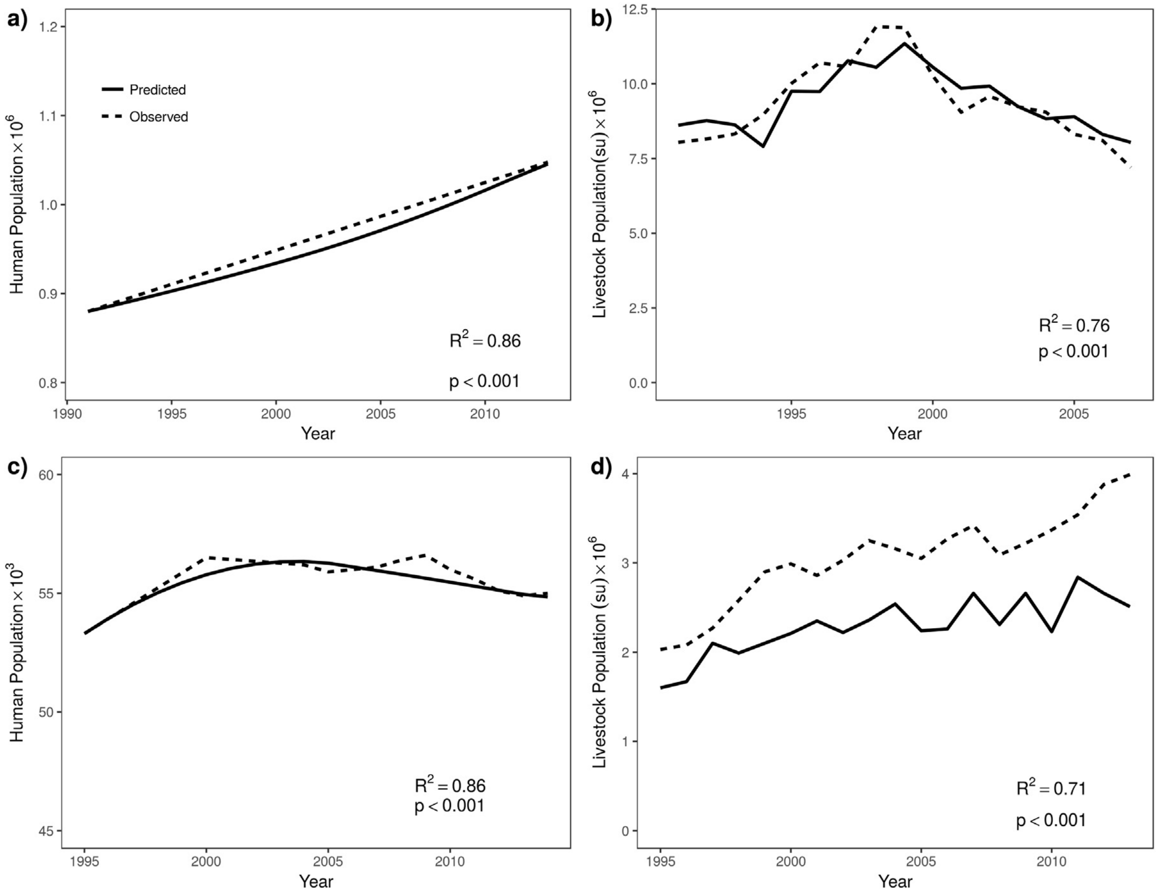

Fig. 3. Model performance against historic data: Observed human and livestock population values plotted against model predicted values for Xilingol, Inner Mongolia (a,b) and Sukhbaatar, Mongolia (c,d).

3.3. Alternative scenarios

3.3.1. Xilingol

Several key findings or trends were robust through all scenarios for Xilingol. Livestock population is projected to decline under all scenarios.

The projected steady decrease in livestock population over time alleviates degradation pressure on the grasslands even under fairly different precipitation regimes (Fig. 4a, Base and Scenario1 exhibit similar trends). However, that trend is contingent on the continuation of the current policies in Inner Mongolia that promote protection and restoration of grasslands (via grazing prohibitions and active restorations). In the absence of these policies grassland area declines steadily (Fig. 4a; Scenarios 2,4)

The amount of biomass remaining at the end of the year, per unit grassland, generally trends upward in all scenarios, except under Scenario 4, although there is a large year-to-year variability in biomass in all projections. Biomass is estimated by the model to rise over time under all climate scenarios, even those with declining precipitation trends. This is due to the effect of decreasing rural population on livestock numbers and grazing pressure, which is greater than the effect of the drier climate on available biomass. Under Scenario 4, where rural population increases rather than declines, rural labor increases result in an increased livestock population density and higher grazing pressure, and thus lower biomass remaining at the end of the year (Fig. 4).

3.3.2. Sukhbaatar

In Sukhbaatar, the projected population of livestock in 2050 varies across the scenarios (Fig. 5). The highest future livestock population is projected under Scenario 2, while the projections for Scenarios 1 and 3 do not increase significantly beyond current numbers, although there is great year-to-year variation across all scenarios. Higher urban population growth rates and out-migration under Scenarios 1 and 3 lead to a lower rural population. Livestock population is tied to the size of the rural herding labor force in this model, so declines in rural population moderate the livestock population increase.

The highest rate of livestock population growth was observed under the scenario that simulates investment in rural infrastructure and enhanced mobility of livestock (Scenario 2). The retention of rural labor and increased labor efficiency in this scenario underlie the increased livestock population. The increase in livestock and that trend corresponded with predicted decreases in remaining biomass over time in Scenario 2, due to the increasing grazing pressure.

Scenario 3, which considers the effect of increased privatization of natural resources, without enhancing access to mobility, results in a decline in grassland area, despite the stabilization of livestock population. Projected remaining biomass is variable across the simulation but does not decline significantly.

3.3.3. Urbanization scenarios

Model projections for all three key variables, grassland area, livestock population and biomass, are affected by the rate of

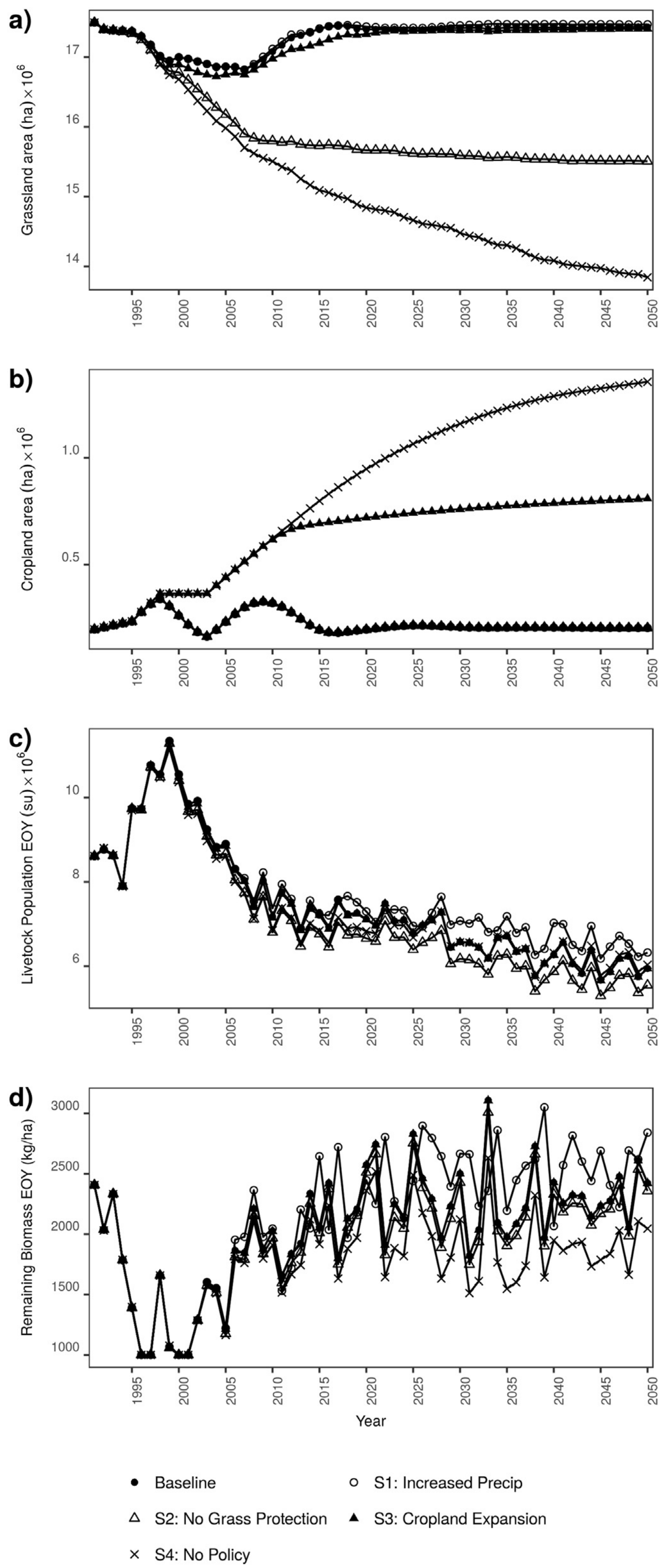

Fig. 4. Model outputs for Xilingol League and comparison of scenarios. Comparison of model behavior under the base model and scenarios 1, 2, 3, and 4 for (a) grassland; (b) cropland; (c) livestock; and (d) biomass per unit grassland remaining at the end of the year. See text for description of scenarios. Maximum urbanized fraction of the population (UFs) = 0.75 for Base and Scenarios 1, 2 and 3; UFs = 0.65 for Scenario 4.

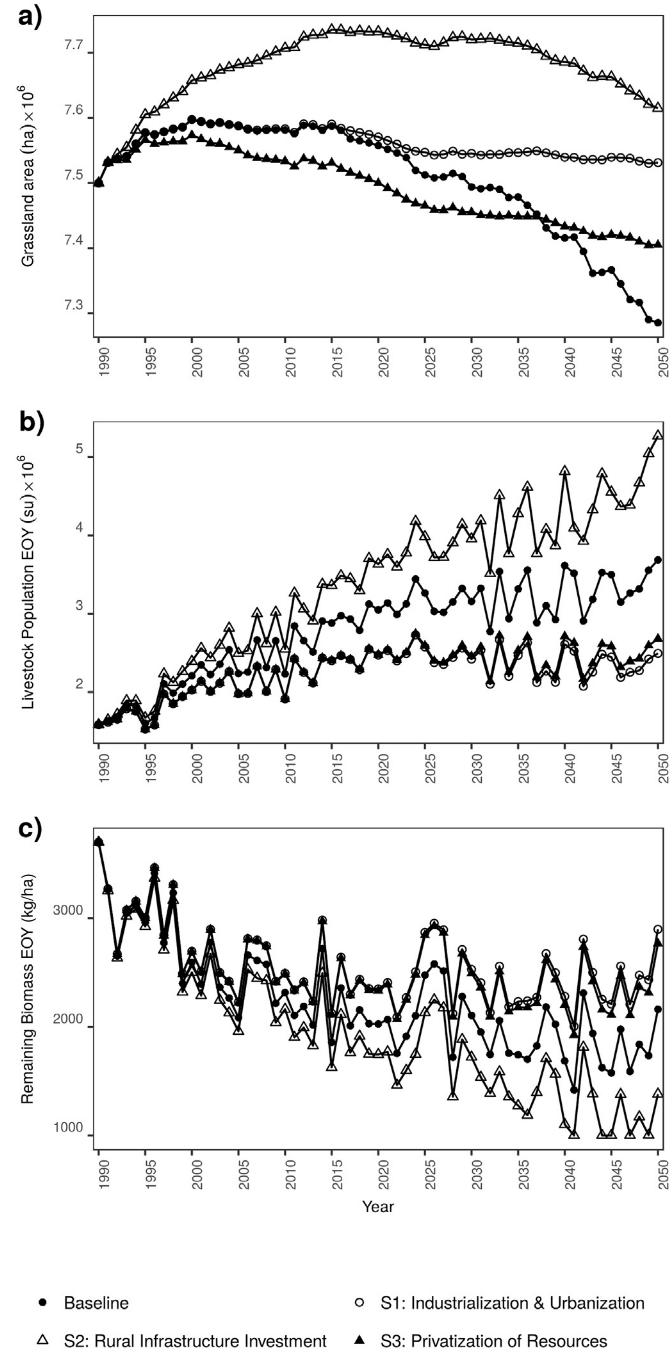

Fig. 5. Model outputs for Sukhbaatar Aimag. Comparison of model behavior under the base model and scenarios 1, 2, and 3 for (a) grassland; (b) remaining biomass per unit of grassland at the end of the year; (c) livestock population. Maximum urbanized fraction of the population (UFs) = 0.65 for all simulations. See text for descriptions of the scenarios and Fig. 6 for projections under alternate urbanization rates.

urbanization (Fig. 6). All three variables were sensitive to the assumed rates of urbanization, but the effects differed across scenarios and study sites.

Changes in UF_s resulted in large differences in model projections for livestock and biomass, but the relative effects were similar across all four scenarios. The impacts of changes in UF_s were more varied in how it impacted projected Grassland area. Scenario 1 and Scenario 3 were not sensitive to changes in UF_s, but Scenarios 2 and 4 had the lowest projected Grassland Area under the low urbanization setting ($UF_s = 0.60$).

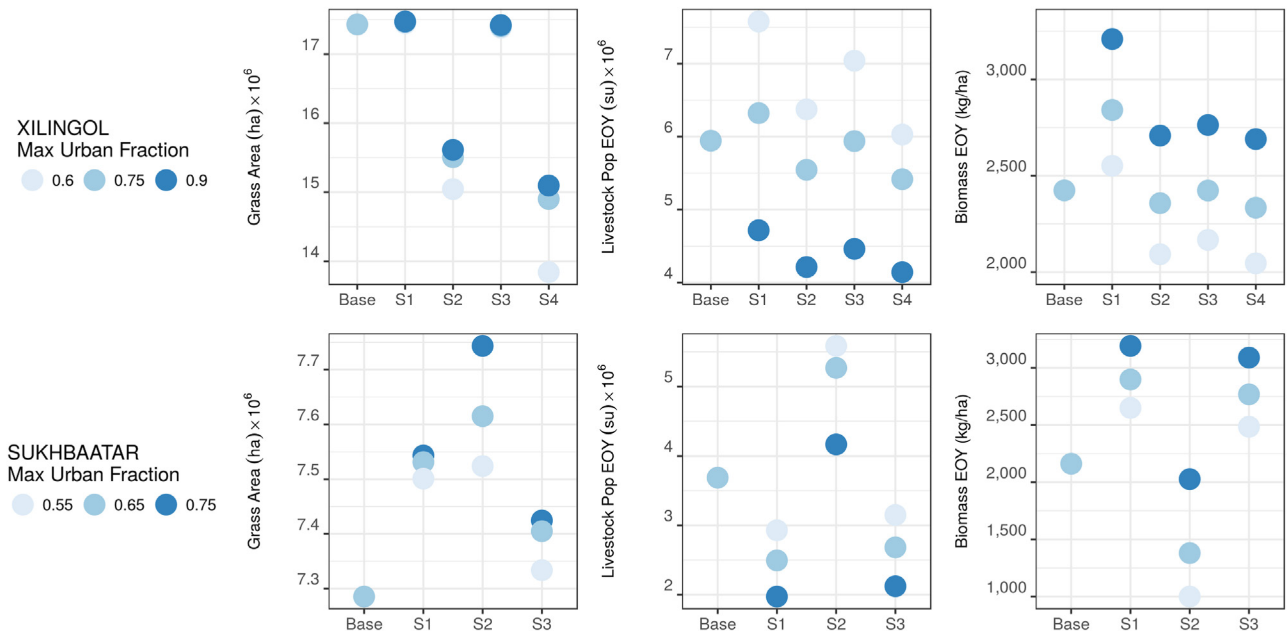

Fig. 6. Variation in model projections by 2050 for three key variables under different assumptions of the long-term maximum urbanization: low, medium, and high. Xilingol = 60%, 75%, and 90%; Sukhbaatar = 55%, 65%, and 75%.

Across all three scenarios, the highest urbanization setting ($UF_s = 0.75$) results in the highest projected grassland area, the lowest livestock population and subsequently, the lowest available biomass. But the relative impact of changes in UFs varies across the scenarios. Shifts in UFs in Scenario 1 resulted in fairly similar grassland area projections in 2050 and under Scenario 2 the spread between projections was much greater.

4. Discussion

Our results present somewhat hopeful predictions for the future resilience of the rangelands of the Mongolian Plateau. However, this resilience is dependent on two factors, namely the continuation of grassland protection policies in China and continued rural out-migration in both countries. It is unclear how sustainable this urban migration might be, and how such a demographic shift might affect food security or increasing demand for arable lands in the region.

Our simulations suggest that future dynamics in the two systems are strongly influenced by urbanization trends, which alter the spatial distribution of the population, the area of urban settlements, and the makeup of the rural workforce available for herding (Fig. 7). With a decline in rural population there is also an expected decline in rural labor available for herding, and thereby a decrease in the livestock demand for biomass. Decreased biomass consumption affects the rate at which grassland converts to degraded land, and vice versa. However, despite losses in rural populations, livestock numbers in Mongolia as a whole have reached record highs in recent years, rebounding to even greater numbers after each recent dzud event (Fig. 5), likely due in part to increased labor efficiency. Increasing urban population creates demand for more developed land, though the absolute amount land demand is relatively low as the population densities are high.

Increases in livestock population despite declining rural population could also be possible if migrating households are leaving some or all of their livestock behind in rural areas (Fernan, 1999; Li and Huntsinger, 2011). In the past, rural households have relocated many of their members to cities, but maintained herds in the countryside by hiring laborers or by leaving family members behind, but those numbers had been declining (Dorligsuren, 2010). In future work, we need spatial data on how changes in settlement patterns in Mongolia are affecting the distribution of grazing pressure on the landscape, both locally at the aimag and soum level, and nationally because of the high percentage of migration to Ulaanbaatar. We have aggregate census data on total livestock numbers, but to date there are no finer scale spatial data on livestock distribution or density.

Scenario 2 in the Sukhbaatar model, which simulated a future with increased investment in rural infrastructure, exhibited continued grassland persistence despite continued increases in livestock population. This outcome lends credence to calls by some policy makers in Mongolia to push for more focus on strengthening rural herding institutions and cooperatives, in order to support sustainable livestock management, particularly if recent livestock population growth trends continue.

Additionally, our scenarios point to the importance in IMAR of the policies promoting grassland protection via grazing restrictions and policies limiting cropland expansion in affecting grassland dynamics (Buhechaolu, 2005; Hua and Squires, 2015). These policies have strongly affected the amount of grassland area, but we modeled them in a coarse way, by establishing strict targets for grassland (minimum) and cropland (maximum) area, and by tying grassland conversion explicitly to urban population growth. In reality, the broad-scale policies influencing the protection and restoration of grazing land are often implemented and administered at the local level with a great deal of variability that we were not able to incorporate into the model. Regional policies in Inner Mongolia concerning agricultural land conversions could also change in the future to address potential concerns over food production for the growing population; either via conversion to cereal crops or high intensity plantings of fodder to supplement livestock (Wang et al., 2013a). Meat consumption is increasingly rapidly in China (Gale, 2015), but use of regional livestock to supply that demand may require investment in additional infrastructure to enhance access to markets and movement of goods (Briske et al., 2015). Future modeling and empirical work on this topic would benefit from breaking down these multi-scale interactions to further understand how individual decisions by both land holders

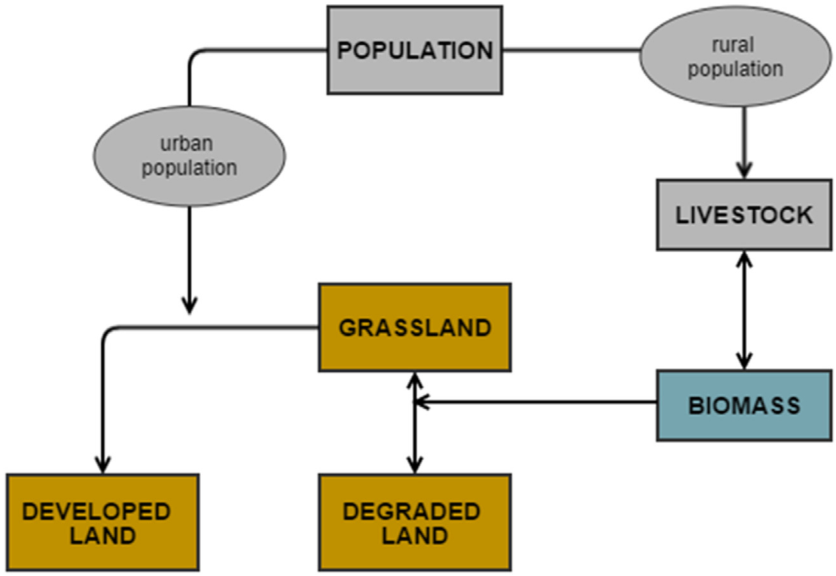

Fig. 7. Schematic of the connections between urbanization, livestock population, and the availability of grassland area. Urbanization influences the availability of grassland both directly, through the conversion of grassland to settlements and other developed areas, and indirectly by affecting the size of the rural population. Rural population influences the number of livestock in a given area and (among other factors) the level of biomass removal and potential degradation of grassland.

and governmental regulators are affected by external factors such as migration and the economy (e.g., Wang et al., 2013a).

Despite the simplifications, model results fill an important knowledge gap. Previous empirical work across IMAR has quantified the impacts of policies restricting grazing on vegetation and soil recovery (Chen et al., 2012; Hao et al., 2014). But aside from noting the treatment, there is nothing linking these studies to the broader social-ecological system with which they interact. By considering resilience of grassland as only a biophysical problem, this earlier work isolates grasslands from their socio-political context as a part of a coupled-human-natural system. Grazing and herding households have been key actors and influencers in these systems for millennia. Attempts to consider the availability of grassland resources into the future must include the interaction of social and ecological forces. Future work could use the system dynamics approach to consider how traditional practices and herder choices interact with new policies to affect grasslands over long term. The work presented here is a step toward explicitly linking our knowledge of vegetation ecological processes with broader changes in land cover and livelihoods on the Plateau.

This work also provides nuance to our current understanding of the role of urbanization in shaping the future of rangeland health. Urbanization is often perceived as a cause of grassland loss, due to conversion of pasture land to development, as has been documented elsewhere in the country (e.g., Seto, 2011; Xie et al., 2005). Our analyses of current dynamics on the plateau and scenario-based simulations show that the effects of future urbanization may be more complicated. This raises several key socio-ecological questions that need to be addressed. The movement of people toward urban centers is shifting grazing pressures spatially, creating increased pressure in peri-urban areas with increased intensity and more degradation in those zones. It remains to be seen how this spatial reorganization of grazing pressure will affect the functioning of the grassland system as a whole, or the provision of ecosystem services across space and time. There have also been recent shifts in herd structure and composition, both in rural and peri-urban regions, in response to global demand for cashmere and climate uncertainties (Hua and Squires, 2015). These changes will necessarily affect decision making about herding practices and more research is needed to understand how these shifts will interact with changes in human population dynamics and climate to affect the rangelands on the Plateau.

Finally, "grassland area" as a variable generalizes a great deal of on-the-ground variability in cover, species composition, and productivity. Our reliance on this less-than-ideal metric stems from and highlights the paucity of data on land cover in arid rangelands in general. Our ability to adequately model drylands is limited by our ability to accurately portray and capture land-cover changes over time. Currently available land cover data products, such as MODIS 12Q or Globcover, are known to have poor accuracy in arid systems, particularly on the Mongolian Plateau (Bontemps et al., 2011; Friedl et al., 2010). This makes it difficult to obtain reliable information on land-cover change over time, particularly concerning transitions between grassland and cropland. In addition to uncertainties in maps of grassland versus cropland area, a classification of grassland does not yield helpful information on the status of the vegetation or soils—which is necessary to understand its health or level of degradation— or the relative trajectory of cover at a particular site. There is an urgent need for more detailed data on land-cover and land-use in arid grassland systems in the region and globally at finer scales. Such data could provide support for research on the effects of policy and environmental change on spatial patterns of grassland impact.

While the advantage of system dynamics modeling is its explicit treatment of time dynamics, a key disadvantage is that it takes an aspatial approach to understanding a phenomenon that clearly has a spatial dimension. Thus, spatial variability in things like climate or market access, and the interactions of those variables across space, must be compressed into single measures over time. While we can incorporate statistical variability or uncertainty of a parameter into the simulations, the impacts of their spatial distributions are not easy to assess with these models. For instance, a distinct aridity gradient extends across the study area, with higher average precipitation in the northeastern portion of the region, which is largely meadow steppe, compared to the far western portion of the region, which is desert steppe. These differences in water availability drive differences in plant community composition, herder behavior, and ultimately the relative response of grasslands to grazing and climate pressures in as described in non-equilibrium theories of rangelands (Fernandez-Gimenez, 1999). We recognize that in adopting an aspatial approach to modeling the system we must necessarily generalize some important changes that are happening across the region. However, our models provide a framework that can be extended to other parts of the region to explore the possible effects of these differences by focusing on other administrative units.

The advantages of the SD modeling approach, in terms of incorporating disparate data types over long time periods, and providing flexibility to explore alternative scenarios, allowed us to examine linkages between multiple aspects of this rangeland system, and uncover robust connections between the human, natural, and land-use subsystems that could not be considered in a traditional ecological model.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2016.11.005.

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Further reading

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